

UNITED STATES PATENT APPLICATION

of

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for

**A METHOD FOR IMPROVING HOLE MOBILITY ENHANCEMENT IN STRAINED
SILICON P-TYPE MOSFET**

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PRIORITY INFORMATION

5 This application claims priority from provisional application Ser. No. 60/391,452
filed June 25, 2002, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

 The invention relates to the field of p-type MOSFETS, and in particular to
10 improving hole mobility in strained silicon p-type MOSFETS.

 Strained silicon grown on relaxed $\text{Si}_{1-x}\text{Ge}_x$ virtual substrates has been used to
fabricate both *n*- and *p*-type MOSFETs, which exhibit enhanced carrier mobility
compared to bulk silicon. Biaxial tensile strain breaks the six-fold degeneracy of
silicon's conduction band, resulting in reduced intervalley scattering in nMOS devices.
15 Furthermore, for in-plane transport, electrons have only the low transverse effective mass
($m_t=0.19m_0$). For ϵ -Si grown on $\text{Si}_{0.8}\text{Ge}_{0.2}$, the conduction band splitting is large enough
to completely suppress intervalley scattering, and no further improvement in electron
mobility is gained by increasing the strain in the silicon layer.

 Biaxial tensile strain also splits the light-hole/heavy-hole degeneracy in the
20 valence band. Unlike the conduction band, strain also changes the shape of the light-hole
valley, resulting in lower in-plane and out-of-plane effective masses. Since the rate of
subband splitting in the valence band is known to be lower than for the conduction band,
theory predicts that intervalley scattering for holes will not be suppressed until the strain
reaches 1.6%, corresponding to growth on a $\text{Si}_{0.6}\text{Ge}_{0.4}$ buffer. Recent experimental work

shows that hole mobility enhancement saturates for ϵ -Si on $\text{Si}_{0.6}\text{Ge}_{0.4}$, with no further improvement as the virtual substrate Ge content was increased to 50%.

Unlike ϵ -Si nMOS, mobility enhancements in ϵ -Si p-type MOSFETs demonstrate a functional dependence on vertical effective field. While an 80% electron mobility enhancement has been observed in ϵ -Si for vertical fields ranging from 0.1 to 1MV/cm, hole mobility enhancements tend to evolve as the effective field changes, as shown in FIG. 1. For low fields, the hole mobility enhancement typically increases as the vertical field increases. At an intermediate field value, the enhancement peaks and then degrades with further increases in field.

SUMMARY OF THE INVENTION

According to one aspect of the invention, there is provided a method of forming a MOSFET device. The method includes providing a substrate. The method includes forming on the substrate a relaxed SiGe layer having a Ge content between 0.51 and 0.80. Furthermore, the method includes depositing on the relaxed SiGe layer a ϵ -Si layer.

According to another aspect of the invention, there is provided a method of forming a MOSFET device. The method includes providing a substrate. Also, the method includes forming on the substrate a relaxed SiGe layer having a Ge content between 0.51 and 0.80. Furthermore, the method includes forming on the relax SiGe layer a digital alloy structure that comprises alternating layers of ϵ -Si and SiGe having a Ge content between 0.51 and 1 so that the mobility enhancement of the device is constant.

According to another aspect of the invention, there is provided a method of forming a MOSFET device. The method includes providing a substrate. The method includes forming on the substrate a relaxed SiGe layer having a Ge content between 0.51 and 0.80. Furthermore, the method includes depositing on the second SiGe buffer a ϵ -Si layer so that hole mobility enhancement increases with effective field.

According to another aspect of the invention, there is provided a MOSFET device. The MOSFET device includes a substrate. A relaxed SiGe layer is formed on the substrate having a Ge content between 0.51 and 0.80. A ϵ -Si layer is deposited on the relaxed SiGe layer.

According to another aspect of the invention, there is provided a MOSFET device. The MOSFET device includes a substrate. A relaxed SiGe layer is formed on the substrate having a Ge content between 0.51 and 0.80. A digital alloy structure is formed on the relaxed SiGe layer comprising alternating layers of ϵ -Si and SiGe having a Ge content between 0.51 and 1. The mobility enhancement of the device is constant.

According to another aspect of the invention, there is provided a MOSFET device. The MOSFET device includes a substrate. A relaxed SiGe layer is formed on the substrate having a Ge content between 0.51 and 0.80. A ϵ -Si layer is deposited on the relaxed SiGe layer so that hole mobility enhancement increases with effective vertical field.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a graph demonstrating mobility enhancement as a function of vertical effective field in ϵ -Si p-type MOSFETs;

FIG. 2A is a XVTEM diagram demonstrating a ϵ -Si layer grown on a $\text{Si}_{0.3}\text{Ge}_{0.7}$ buffer; FIG. 2B is a graph demonstrating mobility enhancement of ϵ -Si layer on $\text{Si}_{0.3}\text{Ge}_{0.7}$ pMOSFET compared to other high-mobility ϵ -Si pMOS structures; and

FIG. 3A is a XVTEM diagram demonstrating a ϵ -Si/ $\text{Si}_{0.3}\text{Ge}_{0.7}$ digital alloy structure grown on a $\text{Si}_{0.3}\text{Ge}_{0.7}$ buffer; FIG. 3B is a graph demonstrating mobility enhancement of ϵ -Si/ $\text{Si}_{0.3}\text{Ge}_{0.7}$ digital alloy pMOSFET compared to a convention ϵ -Si structure.

DETAILED DESCRIPTION OF THE INVENTION

While the benefit gained from suppression of intervalley scattering appears to be saturated in ϵ -Si pMOS, further boosts in hole mobility enhancement should be possible by continuing to increase the Ge content in the relaxed SiGe buffer. This is due to the effective mass of holes in the vertical direction is very low, meaning that some part of the hole's wave function is likely to be present below the ϵ -Si surface channel, even at high vertical fields. Since the band structure of $\text{Si}_{1-x}\text{Ge}_x$ rapidly becomes Ge-like at $x=0.7$ to 0.75, the hole effective mass in a relaxed $\text{Si}_{1-x}\text{Ge}_x$ alloy likewise starts to resemble the low hole effective mass measured in pure Ge. The invention includes techniques to increase the hole mobility enhancement in ϵ -Si pMOS as well as methods for controlling the enhancement as a function of vertical effective field.

Relaxed graded SiGe buffers are grown on a crystalline Si substrate to a Ge content of 60% via ultrahigh vacuum chemical vapor deposition (UHVCVD). In other embodiments, the substrate can be a crystalline Si substrate and a relaxed SiGe graded layer, a crystalline substrate and an insulating layer, or the like. The wafers are then

removed from the system and subjected to chemo-mechanical polishing (CMP) to remove crosshatch surface roughness and to reduce the density of dislocation pileups. At this point, the relaxed SiGe layer may be transferred to an alternative substrate, such as an SOI wafer, or left as-is. After recleaning, the wafers are reinserted into the UHVCVD for further grading and device layer deposition. A structure 2 is grown comprising of a 45Å ϵ -Si layer 4 on a $\text{Si}_{0.3}\text{Ge}_{0.7}$ relaxed graded buffer 6, as shown in FIG. 2A, and fabricated into long-channel MOSFETs, which utilize a deposited low temperature oxide as the gate dielectric and a single mask level for device patterning. The buffer 6 can have Ge concentrations between 0.51 and 0.8 for effective operation of the invention..

The inversion layer effective mobility is extracted from the linear regime I-V characteristics. The hole mobility enhancement is a function of vertical effective field for this structure, as shown in FIG. 2B, along with other high mobility ϵ -Si pMOSFETs. As can be seen, the hole mobility enhancement in the ϵ -Si on $\text{Si}_{0.3}\text{Ge}_{0.7}$ pMOSFET increases with effective vertical field over a wide field range and saturates at a value of around 2.5. This novel behavior is useful, because it allows for improved pMOSFET performance in deeply scaled devices with large vertical fields. When the inversion layer first forms at low vertical effective fields in this device, the hole wave function is weighted towards the Ge-rich relaxed buffer because of the large valence band offset between strained Si and SiGe (type II alignment).

Mobility enhancement in this regime probably results from the low effective mass of holes in the $\text{Si}_{0.3}\text{Ge}_{0.7}$ compared to bulk Si. However, because the $\text{Si}_{0.3}\text{Ge}_{0.7}$ is relaxed, its valence band is degenerate and intervalley scattering is present as a mobility limiting mechanism. As the gate overdrive is increased, the centroid of the wave function is

pulled closer and closer to the surface. This shifting of the hole wave function towards the surface ϵ -Si layer adds the benefit of valence band splitting, resulting in mobility enhancements exceeding those previously seen in ϵ -Si p-type MOSFETs. Even as the wave function approaches the surface, a significant portion of the wave function's tail should always be present in the relaxed $\text{Si}_{0.3}\text{Ge}_{0.7}$, because the Si cap is so thin. In this particular demonstration, the Si cap was 45Å thick, thinner layers provide similar benefits. If the Si cap is grown thick enough to contain all or most of the hole wave function, the hole will lose contact with the $\text{Si}_{0.3}\text{Ge}_{0.7}$ at high vertical field and some enhancement will be lost. N-MOSFETs with enhanced electron mobility can also be fabricated on the same wafers, making these materials suitable for enhanced-performance CMOS applications.

A second structure 8 is grown on a relaxed $\text{Si}_{0.3}\text{Ge}_{0.7}$ buffer, except that instead of simply capping the structure with ϵ -Si, the digital alloy 10 consisting of 7 periods of alternating ϵ -Si 12 and $\text{Si}_{0.3}\text{Ge}_{0.7}$ 14 layers is grown, as shown in FIG. 3A. Each layer 12, 14 is approximately 8Å thick, and the entire structure 8 is capped with 20Å of ϵ -Si in order to allow the use of a SiO_2 gate. When the inversion layer forms in this structure 8, the hole should have enhanced transport from the splitting of the valence band degeneracy as long as the hole wave function is within 120Å of the surface. The SiGe layers 14 can have Ge concentrations between 0.51 and 0.8.

As can be seen in FIG. 3B, the mobility enhancement in this device demonstrates no dependence on vertical effective field. This represents a substantial improvement over prior art ϵ -Si p-MOSFETs, where a constant mobility enhancement had previously been thought to be unattainable. Thus, unlike the conventional ϵ -Si p-type MOSFET, the

digital alloy device does not need to be biased to high vertical field in order for the hole wave function to combine reduced intervalley scattering with the Ge-like effective mass of $\text{Si}_{0.3}\text{Ge}_{0.7}$. In general, periodic, repeating layer structures (such as the digital alloy described here) are useful for allowing the hole mobility enhancement to be fixed at a constant value with respect to effective field. n-MOSFETs with electron mobility comparable to Cz-Si can also be fabricated from the same digital-alloy material.

It is important to note that despite the fact that the individual layers 12, 14 are extremely thin, the hole is not experiencing the valence band structure of a random alloy. If the valence band structure is that of the average composition of the layers, then the digital alloy could be replaced by a tensile $\text{Si}_{0.65}\text{Ge}_{0.35}$ layer on a $\text{Si}_{0.3}\text{Ge}_{0.7}$ buffer. However, according to recent alloy scattering studies, such a structure would actually exhibit hole mobility below that of bulk Si.

Even though valence band splitting in ϵ -Si saturates for buffer compositions greater than 40% Ge, further mobility enhancements in ϵ -Si p-type MOSFETs are possible through the use of a high Ge content relaxed buffer. The large enhancements seen at high vertical fields result from a hybrid of the valence band splitting present in the ϵ -Si cap and the Ge-like effective mass in the $\text{Si}_{0.3}\text{Ge}_{0.7}$ buffer. Since the ϵ -Si layer is only 45Å thick, the hole wave function can always sample the relaxed $\text{Si}_{0.3}\text{Ge}_{0.7}$ buffer, even as the hole wave function is pulled towards the surface by the vertical field.

The digital alloy 10 is a structure designed and grown consisting of alternating layers of $\text{Si}_{0.3}\text{Ge}_{0.7}$ and ϵ -Si upon a $\text{Si}_{0.3}\text{Ge}_{0.7}$ buffer. The alternating layer structure 10 allows the hole wave function to sample both the low effective mass in $\text{Si}_{0.3}\text{Ge}_{0.7}$ and the valence band splitting in the ϵ -Si at both low and high vertical field. The use of different

compositions in the alternating layers can also lead to greatly enhanced hole mobility. Even though the layers 12, 14 comprising the digital alloy are on the order of several atomic layers thick, the hole is able to combine the unique benefits intrinsic to each "digit" of the alloy.

5 Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

- What is claimed is: